Demonstration of a compact 100 Hz, 0.1 J, diode-pumped picosecond laser

A. H. Curtis,[1,2,*] B. A. Reagan,[1,2] K. A. Wernsing,[1,2] F. J. Furch,[1,3] B. M. Luther,[1,2] and J. J. Rocca[1,2,3]

[1]*National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology, Colorado State University, Fort Collins, Colorado, 80523, USA*

[2]*Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado, 80523, USA*

[3]*Department of Physics, Colorado State University, Fort Collins, Colorado, 80523, USA*

**Corresponding author: ahcurtis@lamar.colostate.edu*

Received April 6, 2011; accepted April 29, 2011;
posted May 10, 2011 (Doc. ID 145458); published June 1, 2011

We have demonstrated an all-diode-pumped Yb:YAG chirped pulse amplification laser that produces 100 mJ pulses of 5 ps duration at 100 Hz repetition rate. The compact laser system combines a room-temperature Yb:YAG regenerative amplifier for increased bandwidth and a cryogenically cooled Yb:YAG four-pass amplifier for improved heat dissipation and increased efficiency. The optical efficiency of this amplifier is higher than that of other diode-pumped systems of comparable energy.

OCIS codes: 140.7240, 140.3480, 140.3615.

The high average power, small size, and narrow emission band of laser diodes make them attractive for direct pumping of solid state lasers. Diode pumping will allow these lasers to operate more efficiently and at higher repetition rates than conventional flashlamp-pumped systems, in smaller setups. There is great interest in the development of chirped pulse amplification (CPA) laser systems pumped by laser diodes for applications ranging from basic research to technology development and inertial confinement fusion. These applications include picosecond pumps for optical parametric chirped pulse amplification [1], and the efficient generation of extreme ultraviolet and soft x-ray radiation on a tabletop [2,3]. We have previously demonstrated an 18.9 nm soft x-ray laser driven by a 1 J all-diode-pumped CPA laser system operating at 10 Hz [2]. Operation of such joule-level all-diode-pumped laser systems at repetition rates of 50 to 100 Hz will allow for the generation of coherent radiation in the $\lambda = 10$–20 nm spectral region with average powers more than an order of magnitude higher than the tens of microwatts currently available [4].

Nearly all of the diode-pumped CPA laser systems demonstrated to date utilize Yb-doped materials, taking advantage of the Yb^{3+} ion's excellent spectroscopic and material properties for pumping with commercially available near-IR laser diodes. In the case of high average power amplifiers, Yb:YAG is most frequently used. Several diode-pumped CPA laser systems have recently been reported [1–3,5–7]. These include thin disk room-temperature Yb:YAG lasers capable of producing 150 mJ at 100 Hz uncompressed [3], and systems producing 25 mJ pulses at 3 kHz [5] and 200 mJ pulses at 10 Hz [1], of sub-2 ps duration. Additionally, several groups have taken advantage of the increased thermal conductivity and decreased saturation fluence of Yb:YAG at cryogenic temperatures [2,6,7]. We have previously reported a diode-pumped Yb:YAG laser that produced 1 J, 8.5 ps laser pulses at 10 Hz repetition rate [2]. Other cryogenic Yb:YAG lasers that produced lower energy pulses on a broad range of repetition rates have also been demonstrated [6,7]. These include an uncompressed 7.5 mJ pulse system at 10 Hz [6], and the generation of 6.5 mJ pulses of 15 ps duration at 2 kHz [7]. Cryo-cooled Yb:YAG has several advantages for high repetition rate operation that include an increased thermal conductivity, a larger stimulated emission cross-section, and a decrease in the thermo-optic and thermal expansion coefficients [8]. Because of the reduction in bandwidth associated with the increase in stimulated emission cross section, the above cryogenic systems have all been limited to pulsewidths longer than 8 ps.

In this Letter, we report a compact all-diode-pumped Yb:YAG CPA laser that combines the advantages of the broader bandwidth of room-temperature Yb:YAG with the excellent thermal properties, high gain, and decreased saturation fluence of cryogenically-cooled Yb:YAG. The laser system produces 140 mJ, centered near $\lambda = 1030$ nm pulses at a 100 Hz repetition rate, which is compressed into 100 mJ, 4.8 ps laser pulses. Figure 1 shows a diagram of the system that consists of a diode-pumped Yb:KYW oscillator, a grating stretcher, two stages of amplification, and a grating compressor. The first amplifier is a high-gain regenerative amplifier in which the gain medium is a Yb:YAG crystal at room

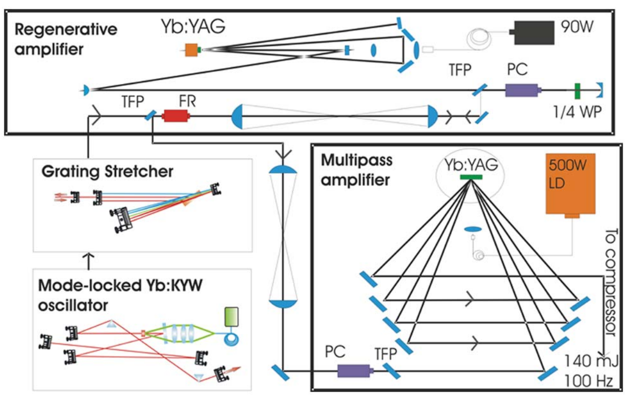

Fig. 1. (Color online) Schematic diagram of the compact, diode-pumped Yb:YAG laser system. FR, Faraday rotator; PC, Pockels cell; TFP, thin film polarizer; WP, waveplate; LD, laser diode.

0146-9592/11/112164-03$15.00/0

temperature. The second stage is a multipass, cryo-cooled Yb:YAG power amplifier. The entire system occupies half of a 3.5 m × 1.5 m optical table.

The diode-pumped, mode-locked Yb:KYW oscillator produces laser pulses with ~5 nm FWHM bandwidth centered at 1032 nm at 56 MHz with an average power of 1.2 W. Similar oscillators have been previously demonstrated [9]. This oscillator is pumped by a 30 W, 980 nm, fiber-coupled laser diode. The cavity has a prism pair for dispersion compensation and is mode locked using a semiconductor saturable absorber mirror. The 300 fs pulses exiting the oscillator are stretched in a folded Martinez stretcher. An Offner telescope is implemented to allow for a more compact arrangement, and the stretcher is double passed with respect to the standard folded stretcher configuration to allow for 450 ps FWHM stretched pulses.

Stretched pulses are selected at 100 Hz repetition rate and are injected into the first stage regenerative amplifier as shown in Fig. 1. The active medium of this amplifier is a 1 mm thick, 10 at. % Yb:YAG crystal used in the active mirror configuration. The crystal is wedged at an angle of ~1° to avoid unwanted reflections in the cavity, and is soldered to a water cooled copper heat sink to facilitate efficient heat removal. The crystal is pumped with 2 ms pulses from a 90 W, 940 nm, fiber-coupled laser diode. Pump light exiting the fiber is imaged into a 600 μm diameter spot by a pair of achromatic lenses. The amplifier cavity is designed to have a beam size of ~700 μm FWHM on the laser crystal and to allow two double-passes through the gain region per cavity single-pass. While the alignment of this configuration is more complex, it allows for a significantly higher gain per cavity round trip, increasing the stability and the obtainable pulse energy. Additionally, entering the crystal at different angles reduces the spatial hole burning effects associated with active mirror lasers [10]. Laser pulses are switched in and out of the cavity using the combination of a Pockels cell and thin film polarizer. The center wavelength of the amplified pulses can be tuned over a range of several nanometers by adjusting the angle of a thin film Fabry–Perot etalon with 12 nm FWHM spectral transmission near Brewster's angle. This allows us to tune the peak emission wavelength of the room-temperature Yb:YAG regenerative amplifier to the peak gain of the cryo-cooled amplifier [11]. A Faraday rotator and thin film polarizer are used to separate the exiting amplified pulses. When pumped with 2 ms, 86.5 W pulses, the amplifier generates pulses of 3.6 mJ energy at 100 Hz repetition rate with good mode quality. Under these conditions the cavity requires 16 round trips to achieve the maximum energy. The pulse energy and repetition rate are limited by the pump power available, and only a slight amount of thermal lensing is observed at this energy and repetition rate. Additionally, the regenerative amplifier can be operated at any repetition rate up to 100 Hz, requiring only a minor realignment.

The second amplification stage, schematically shown in Fig. 1, is a four-pass cryogenically-cooled Yb:YAG amplifier. This amplifier uses a "thick disk" active mirror approach, which is a compromise between the highly efficient heat removal of the thin disk approach [12] and the limitations to energy storage imposed by amplified spontaneous emission resulting from the very high transverse gain of low aspect ratio gain geometries. A 4.5 mm thick, 2 at. % Yb:YAG crystal is soldered to a liquid nitrogen filled copper heat sync, which is enclosed in an evacuated enclosure. The Yb:YAG crystal is pumped by 1.5 ms pulses from a 500 W fiber-coupled laser diode emitting at 940 nm. Pump light exiting the 600 μm fiber is imaged onto the crystal by a single achromatic lens to produce a relatively uniform 4 mm diameter spot. 2 mJ laser pulses from the first amplification stage are amplified in four double-passes through the active region. Figure 2 shows the amplified laser pulse energy obtained as a function of peak pump power at 100 Hz repetition rate. At the maximum pump power the amplifier operates in the gain-saturation regime, producing 140 mJ pulses with an optical efficiency of 20%. This optical efficiency exceeds those reported for room-temperature diode-pumped amplifiers producing comparable energy by a factor of 1.5–3 [1,3]. Higher efficiency could be achieved by increasing the fraction of pump power absorbed by the Yb:YAG by increasing the doping, or double passing the pump light. Figure 2 shows that good mode quality is maintained and negligible thermal lensing is observed during the amplification process. The amplifier operates with a shot to shot standard deviation of 0.3% and is stable over a period of several hours without realignment.

Following amplification, the pulses are compressed by a dielectric grating pair with an efficiency of 72%. Figures 3(a) and 3(b) show the spectra and second harmonic autocorrelation traces of the compressed pulses after amplification in the first and second stages. The millijoule pulses from the regenerative amplifier have 0.55 nm FWHM bandwidth and could be compressed to ~3.6 ps FWHM. Gain narrowing in the second cryo-cooled amplification stage results in a 0.35 nm FWHM bandwidth. After compression, 100 mJ pulses are obtained with a duration of 4.8 ps FWHM (sech^2 fit). These pulses approach the transform-limit with a time–bandwidth product of 0.48. Simulations show that there will be negligible further bandwidth narrowing upon subsequent amplification to the joule level.

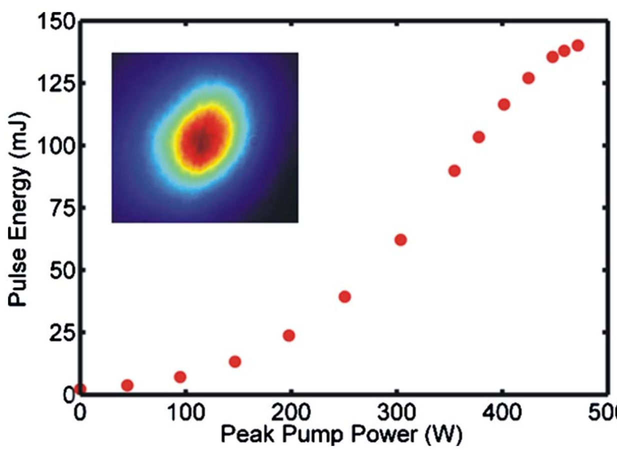

Fig. 2. (Color online) Output pulse energy as a function of pump diode peak power at 100 Hz repetition rate. The optical efficiency of the second stage amplifier is 20%. The inset image shows the 140 mJ beam exiting the amplifier.

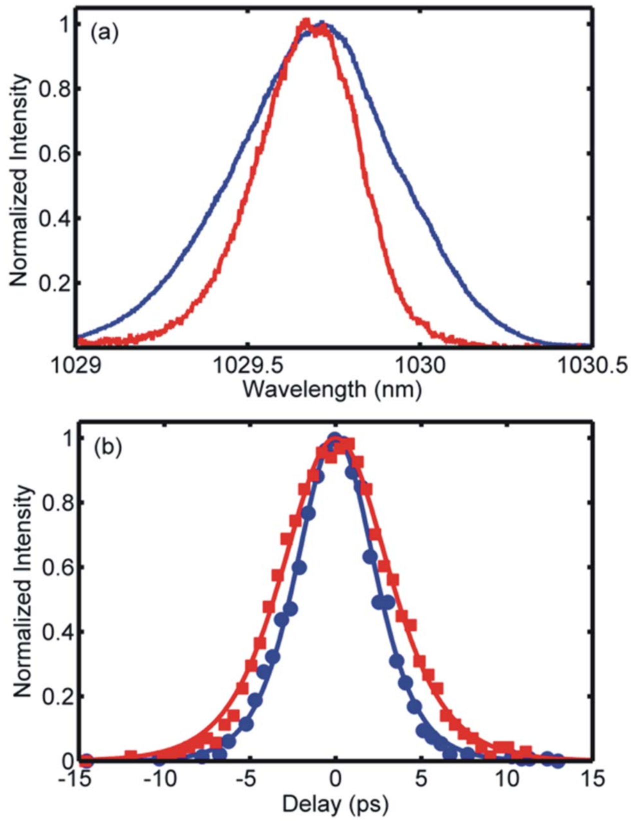

Fig. 3. (Color online) (a) Spectra of laser pulses after the first (thinner blue line) and second (thicker red line) stages of amplification. Pulses exiting the first stage have a bandwidth of 0.55 nm FWHM, which narrows to 0.35 nm FWHM after the second amplifier. (b) Second harmonic autocorrelation traces of compressed amplified pulses after the first (blue circles) and second (red squares) amplification stages. Solid lines are sech^2 fits of the data. Pulses exiting the first stage can be compressed to 3.6 ps FWHM, while amplified 100 mJ pulses are compressed to 4.8 ps FWHM.

In summary, we have developed a very compact and efficient all-diode-pumped laser system that produces 100 mJ pulses of 4.8 ps duration at 100 Hz repetition rate. This was achieved by combining the broader bandwidth of a room-temperature Yb:YAG regenerative amplifier with the excellent thermal properties and high-gain of a cryogenically cooled Yb:YAG power amplifier. With an additional cryo-cooled amplification stage, the system is expected to produce multi-joule laser pulses of 5 ps durations at high repetition rates.

This work was made possible by funding from the Engineering Research Centers Program of the National Science Foundation (NSF) under NSF award EEC-0310717 and previous support from NSF grant number 0521649.

References

1. S. Klingebiel, C. Wandt, C. Skrobol, I. Ahmad, S. A. Trushin, Z. Major, F. Krausz, and S. Karsch, Opt. Express **19**, 5357 (2011).
2. F. J. Furch, B. A. Reagan, B. M. Luther, A. H. Curtis, S. P. Meehan, and J. J. Rocca, Opt. Lett. **34**, 3352 (2009).
3. J. Tümmler, R. Jung, H. Stiel, P. V. Nickles, and W. Sandner, Opt. Lett. **34**, 1378 (2009).
4. D. H. Martz, D. Alessi, B. M. Luther, Y. Wang, D. Kemp, M. Berrill, and J. J. Rocca, Opt. Lett. **35**, 1632 (2010).
5. T. Metzger, A. Schwarz, C. Y. Teisset, D. Sutter, A. Killi, R. Kienberger, and F. Krausz, Opt. Lett. **34**, 2123 (2009).
6. Y. Akahane, M. Aoyama, K. Ogawa, K. Tsuji, S. Tokita, J. Kawanaka, H. Nishioka, and K. Yamakawa, Opt. Lett. **32**, 1899 (2007).
7. K. Hong, J. T. Gopinath, D. Rand, A. M. Siddiqui, S. Huang, E. Li, B. J. Eggleton, J. D. Hybl, T. Y. Fan, and F. X. Kärtner, Opt. Lett. **35**, 1752 (2010).
8. R. L. Aggarwal, D. J. Ripin, J. R. Ochoa, and T. Y. Fan, J. Appl. Phys. **98**, 103514 (2005).
9. P. Klopp, V. Petrov, U. Griebner, and G. Erbert, Opt. Express **10**, 108 (2002).
10. R. Paschotta, J. Aus der Au, G. J. Spühler, S. Erhard, A. Giesen, and U. Keller, Appl. Phys. B **72**, 267 (2001).
11. J. Dong, M. Bass, Y. Mao, P. Deng, and F. Gan, J. Opt. Soc. Am. B **20**, 1975 (2003).
12. A. Giesen and J. Speiser, IEEE J. Sel. Top. Quantum Electron. **13**, 598 (2007).